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REPORT No. 54

**EFFECT OF TEMPERATURE AND PRESSURE ON
THE SPARKING VOLTAGE**



**NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS**



PREPRINT FROM FIFTH ANNUAL REPORT

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EFFECT OF TEMPERATURE AND PRESSURE ON THE SPARKING VOLTAGE

BY

L. B. LOEB and F. B. SILSBEE

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EFFECT OF TEMPERATURE AND PRESSURE ON THE SPARKING VOLTAGE.¹

By L. B. LOEB and F. B. SILSBEE.

RÉSUMÉ.

The investigation described in this report was conducted at the Bureau of Standards for the National Advisory Committee for Aeronautics.

The spark discharge used to fire an internal combustion engine must pass through the compressed and heated mixture which occupies the engine cylinder near the end of the compression stroke. The object of the experiments described in this report was to determine how the voltage necessary to produce such a spark discharge varies with the pressure and temperature of the gas. The results are of value in showing what voltage an ignition system is required to deliver in order to produce a spark and in enabling one to set up in the laboratory a convenient experimental gap electrically equivalent to that in the engine cylinder.

Measurements were made on spark plugs screwed into a bomb containing compressed air, and inserted in an electric furnace so that both pressure and temperature could be varied as desired. The sparking voltages were measured on four plugs, having different electrodes, at pressures up to 100 pounds per square inch and temperatures up to 500° C. Both 60-cycle alternating current and current obtained from a magneto were used. The observed voltages are plotted against pressure in plots 2, 3, 4, and 7, and against density in plot 5.

The results show that the sparking voltage is a linear function of the density of the gas and depends upon pressure and temperature only as they affect the density, i. e., heating a gas at constant volume does not affect the sparking voltage. For a typical spark plug gap set at 0.5 mm. (0.020 inch) the sparking voltage was found to be 2,800 volts at atmospheric density and 9,400 volts at a density five times as great.

The data given in this report were obtained on air only. The results of measurements made elsewhere indicate that the sparking voltage in an explosive mixture of gasoline and air is about 10 per cent less than in pure air, and that the change in voltage is proportional to the amount of gasoline present.

INTRODUCTION.

This report describes some experiments made to determine the change of spark potential with pressure and temperature, in order to determine the necessary minimum potential for causing sparks to pass in a gasoline engine whose compression ratio was known and in which the temperature of the gases before ignition could be estimated.

According to the simple theory (J. J. Thomson, *Conduction of Electricity through Gases*; Townsend, *Electricity in Gases*; and Peek, *Transactions of the American Institute of Electrical Engineers*, 1910-1916) the sparking potential depends solely on the density of the gas between the electrodes for a given fixed pair of electrodes, i. e., on the total number of molecules between the electrodes. This has been investigated over a considerable range of pressures, spark distances, and forms of electrodes by numerous observers, but only three investigators have studied the effect of temperature, and then only over a limited range. They all found that the sparking potential depended solely on the density of the gas over the range studied.

In the study of airplane spark plugs it seemed advisable to determine whether this law held for pressures and temperatures which might occur in the cylinders of a high compression engine

¹ This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 14.

just before the ignition of the charge. In airplane engines the maximum compression pressures under normal conditions range from 90 to 130 pounds per square inch with temperatures up to 300° C.

APPARATUS.

The experiments were conducted as follows: An ordinary $\frac{1}{4}$ -inch Titan A. C. porcelain plug was screwed into a steel bomb about 25 cm. (10 inches) long, having the design indicated in figure 1. There was a thick glass window opposite the sparking terminals when the plug was screwed in position. A high-pressure air tank connected to the bomb through suitable valves served to regulate the air pressure to any desired value. Temperatures were measured by a Pt, Pt-Rh thermocouple, B. S. W5, which was inserted in a steel tube sealed at one end with walls $\frac{1}{2}$ mm. (0.020 inch) thick. This was screwed into the bomb so that its inner end was within 1 cm. of the sparking terminals of the plug. The bomb was placed in a cylindrical electric resistance furnace and packed with asbestos wool, so that only the porcelain insulator was exposed at one end, while the window projected out about 5 cm. (2 inches) beyond the other end.

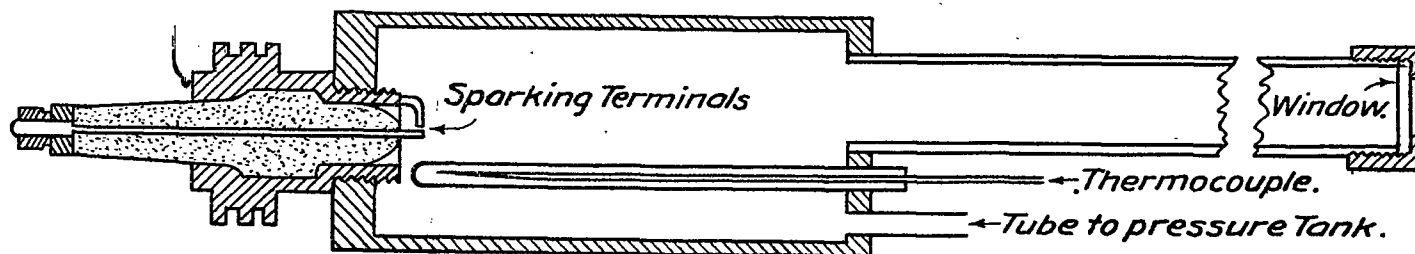
Sixty-cycle voltage was supplied through a step-up transformer having a ratio of 200:1 and applied between the central electrode and the bomb. A resistance of 220,000 ohms was put in series with the plug to avoid an excessive current and consequent burning of the terminals when the spark passed. The voltage was read on a voltmeter connected to the low-tension side of an auxiliary step-down transformer. The passage of the spark was made evident both by the kick of the voltmeter and by the appearance of the spark in the bomb. Ionization was provided for by the use of a half milligram sample of radium in most of the experiments, while in some a 50-mgm. sample, placed just below the electric furnace, was also used. This ionization served to eliminate the complicating effect of spark "lag" and made the readings much more consistent and reliable. No striking difference in the readings could be noticed with the two different samples.

The tests were run on three Titan plugs: No. 1 had the regular terminals of Ni-Mn wire 1.3 mm. (0.051 inch) in diameter set at right angles and separated by 1.8 mm. (0.071 inch); No. 2 was a Titan plug with similar terminals 3.13 mm. (0.123 inch) in diameter rounded at the ends, separated by 1.2 mm. (0.047 inch); No. 3 was a plug like No. 1 but with a distance of 2.2 mm. (0.086 inch) between the wires. In each case the spark passed between the cylindrical surfaces of the wires near the point of closest proximity.

PROCEDURE.

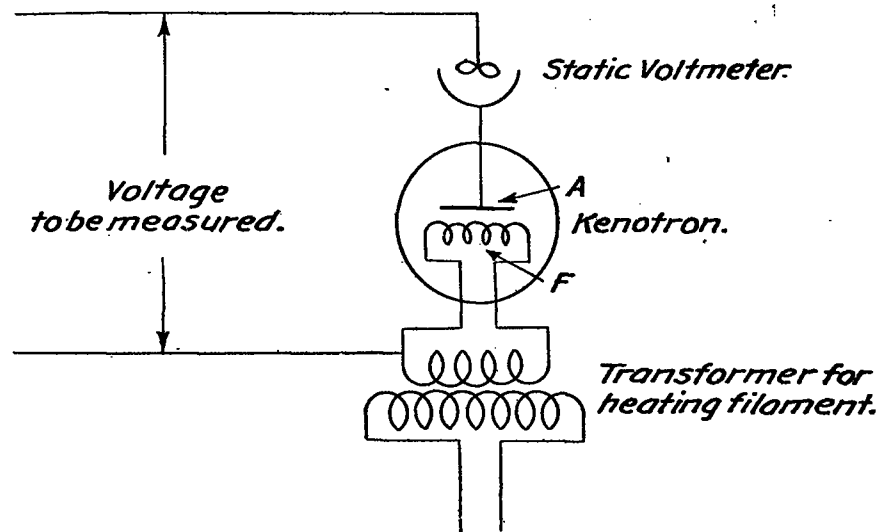
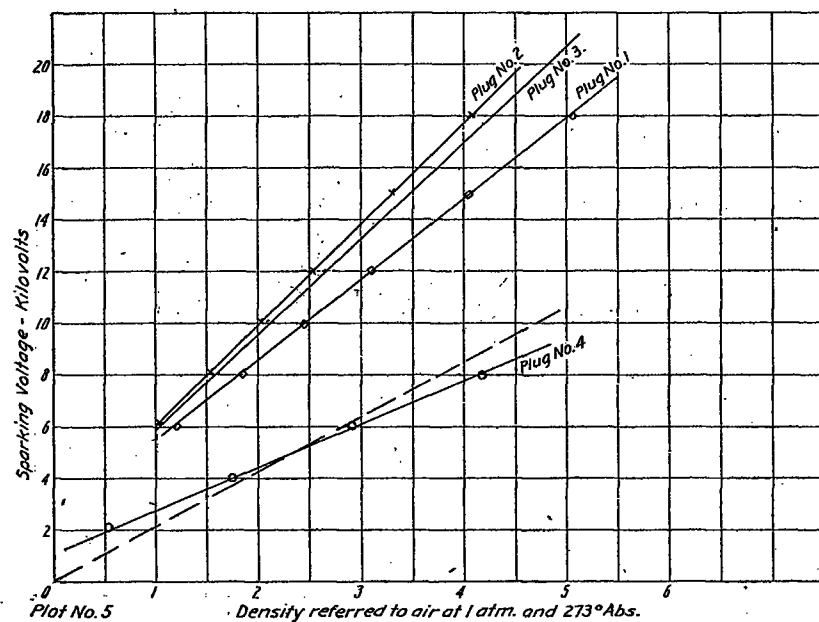
The readings were taken as follows: The temperature was run up to the desired value and held constant from 15 minutes to half an hour. There were fluctuations at the higher temperatures of as much as 10 degrees either way so that a mean temperature was chosen as representing the true conditions. The breakdown voltage of the gap was then determined by at least 10 trials for each pressure. The pressure was increased in steps of 10 pounds per square inch. The pressures were read by two small pressure gauges whose ranges were from 0 to 100 pounds per square inch. The spark potentials were read to as high a pressure as it was possible to obtain without the sparks passing over the outside of the insulator. Then the pressure was reduced in steps of 20 pounds and readings again made. As a whole the return readings checked the first readings well. This can be seen from the plots where maximum sparking voltage is plotted against the pressure for each temperature. As the voltage which could be used without sparking over the outside of the porcelain was about 19,000 volts, no voltages were measured above this. The pressure range over which the measurements could be carried out started from 60 pounds at room temperature and increased until at 200° C., or thereabouts, pressures of 100 pounds could be used.

From then on the pressures were limited with increasing temperatures by a new phenomenon which may have been caused by electron emission from the hot terminals at high voltage. Under these conditions the spark was replaced by a sort of purple brush discharge (corona) which came on gradually as the voltage was increased.



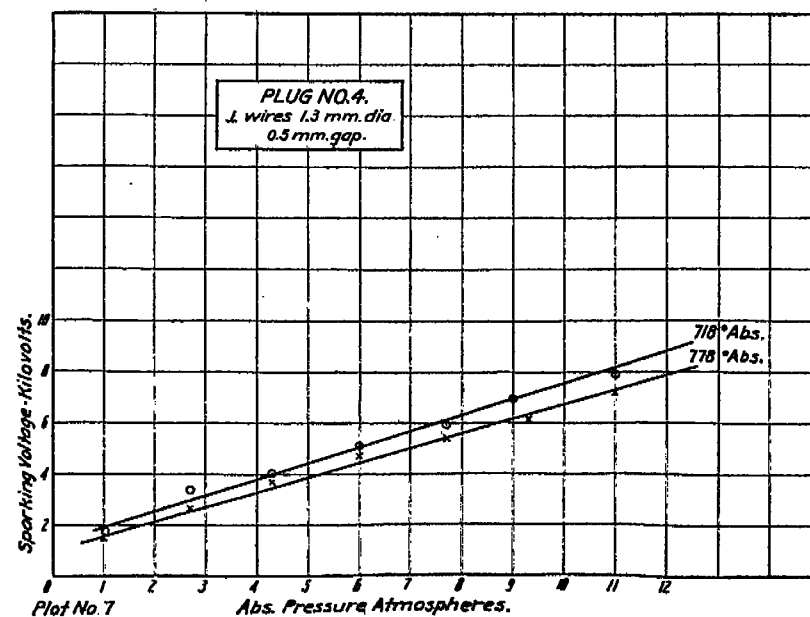
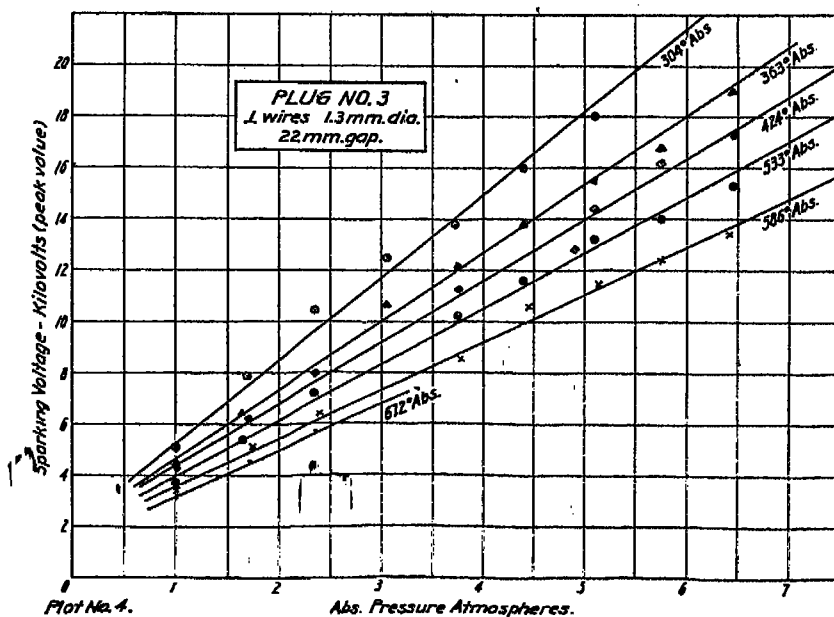
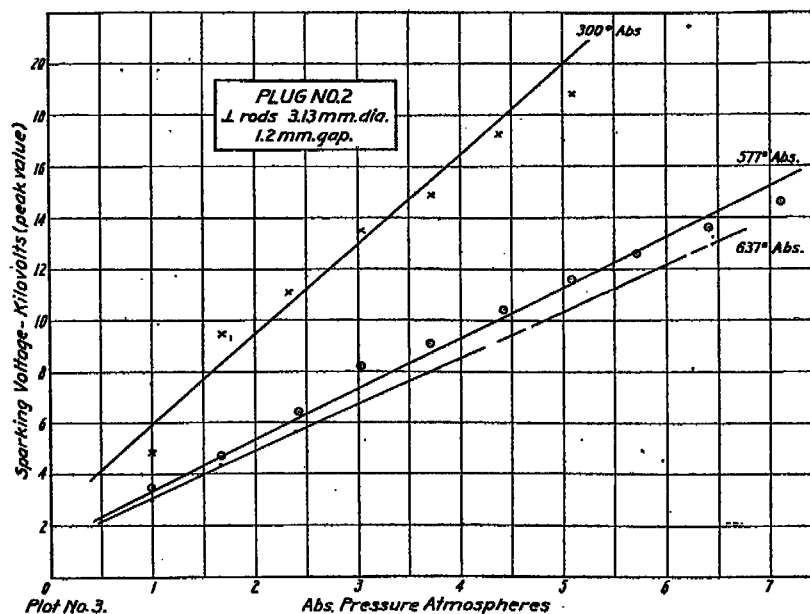
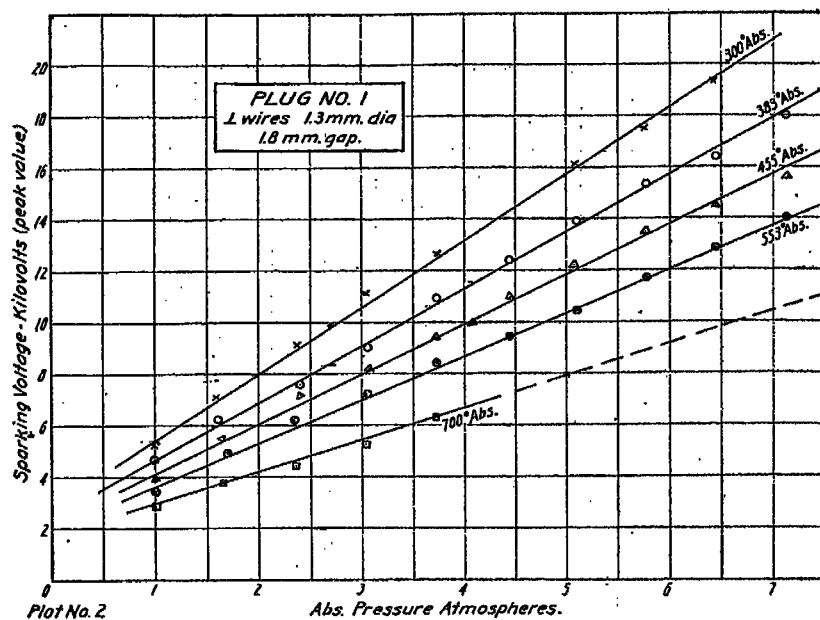
SPARK PLUG BOMB.

Fig No.1



KENOTRON SET-UP.

Fig No.6



It was at first thought that this glow discharge might be an important factor in causing ignition trouble. Further measurements were therefore made in the same apparatus but with a Bosch D-6 magneto as a source of voltage. With this arrangement no brush discharge could be detected although the observations were carried to 760° C. Above 600° C. the electrical conductivity of the porcelain insulator was great enough to prevent the magneto from sparking at the higher pressures, but there was no sign of brush discharge under any conditions. It is probable that a certain time is required for such a discharge to form and that the very sudden application of voltage produced by the magneto does not admit of this.

RESULTS.

The curves plotted between maximum sparking potentials in kilovolts and pressure in atmospheres may be seen in plots 2, 3, and 4. The results represented by all these curves, except the one for low temperature measurement with the larger terminals could be repeated consistently. It is possible that a stronger source of ionization should have been provided, and the voltage increased still more slowly in this case. The slight curvatures of the lines may be due in part to the gauges, since no calibration corrections were applied. The direction of the curvature is the same as that noted by other observers.

The data given in the curves were analyzed by first reading from each of the curves the pressure corresponding to a given voltage, say 10,000 volts. From this pressure and the temperature pertaining to the curve, the relative density of the gas is then computed by the formula:

$$\rho = \frac{\delta}{\delta_0} = 273 \frac{P}{T}$$

where δ_0 is the density at 1 atmosphere and 273° absolute, P is the pressure in atmospheres, and T the absolute temperature in degrees centigrade. This was done for six different voltages on each plug. Table I gives the results on plug No. 1 at 10,000 and 8,000 volts, and is typical of the other data. It is evident that the densities thus obtained are constant within a few per cent over the entire range and show no systematic change with temperature or pressures.

TABLE I.

Temperature Abs.	Density at	
	10,000 volts.	8,000 volts.
300°	2.51	1.83
383°	2.46	1.80
455°	2.27	1.80
553°	2.38	1.78
700°	2.59	1.98
Mean.....	2.45	1.83

It may therefore be concluded that the breakdown voltage is a function of the gas density only. To determine the form of this function the average values of density obtained as described above are plotted against the corresponding voltage in plot 5. The curves thus obtained show that the breakdown voltage is a linear function of the density but is not proportional to it. The data can be represented by the following equations:

Plug No. 1	$E = 2.2 + 3.1 \rho$
Plug No. 2	$E = 1.8 + 4.0 \rho$
Plug No. 3	$E = 2.4 + 3.4 \rho$

Where E is the sparking voltage in kilovolts and ρ is the density relative to air at atmospheric pressure and 0° C. The constants in these equations are of course dependent upon the shape and spacing of the electrodes, and would be smaller for the case of the shorter 0.5mm (0.020 inch) gaps used in spark plugs.

In addition to the measurements with alternating current described above, a second series of tests was made, using a Bosch D-6 magneto as the source of e. m. f. and a special crest voltmeter equipment¹ to measure the breakdown voltage.

This equipment consisted of an Albrecht-electrostatic voltmeter connected in series with a G. E. kenotron (electric valve) as shown in figure 6. This valve permits current to flow when the heated filament *F* is negative with respect to the relatively cold anode *A*, but allows no current to flow in the reverse direction. Consequently, a negative charge accumulates on the insulated conductor, formed by the anode and the case of the electrometer, of such amount that when the sparking electrode and voltmeter needle are at their greatest positive potential the filament and anode are at the same potential, and there is no tendency for further charging. During the rest of the time the needle of the voltmeter is near ground potential, but the rectifying effect of the kenotron prevents the charge from leaking off. Consequently the meter comes to a steady deflection which measures the maximum positive voltage applied.

Runs were made with this apparatus at temperatures of 460° C. and 520° C. up to pressures of 150 pounds per square inch, using a Champion (Toledo) plug No. 4 with X-bend electrodes set with the usual spacing of 0.5 mm. (0.020 inch). The results as obtained are plotted in plot 7 and the combined data from these curves are plotted against relative density in plot 5, giving a line whose equation is

$$E = 1.1 + 1.7\rho.$$

These measurements with the magneto and crest voltmeter showed the presence of a further complication due to the fact that the heat of the spark raised the temperature of the electrodes very materially. This in turn heated the gas near them so that the discharge occurred through gas which was decidedly less dense than the surrounding atmosphere. This was indicated by the fact that at first starting the magneto the voltmeter showed a relatively high voltage (in one case 4,100 volts), which decreased gradually for nearly a minute, after which it remained constant at a much lower value (2,350 volts). The time required for the change implies very strongly that it is a purely thermal effect rather than any ionization due to the preceding sparks, since the latter effect would be almost instantaneous. In the case of a spark plug in an engine cylinder, the central electrode, being insulated thermally as well as electrically by the core, is much hotter than the incoming charge and consequently this effect may be present to some extent.

As a check upon the laboratory data measurements were also made in a Hall-Scott A-5 aviation engine having a compression ratio of 4.2:1. Owing to the late closing of the intake valve and the advance of the spark, the actual ratio of cylinder volume at intake to that at ignition was only 3.2:1. If it can be assumed that the charge in the cylinder is at atmospheric pressure and temperature at the closing of the intake valve, then the relative density at ignition will be 3.2. Plug No. 4 was run in this engine firing from a Dixie "88" magneto. The crest voltage as measured by the kenotron was found to be 5,950 volts. Measurements with a calibrated spark gap having 1 cm. spheres indicated 4,500 volts. The voltage predicted for this density from figure 5 is 6,400 volts.

In comparing these results it must be borne in mind that the crest voltmeter loses its charge very slowly, so that it really indicates the highest peak occurring during two or three minutes preceding the reading. The parallel spark gap, on the other hand, is adjusted to fire about half the time and probably gives more nearly the average crest voltage. It appears, therefore, that the results obtained in the laboratory are in substantial agreement with those found on the engine, and that the linear relation between voltage and density may be safely applied to ignition circuits.

It will be noted that the results shown in plot 5 can be represented roughly by a straight line through the origin, such as is shown dotted, and which indicates a direct proportionality between the sparking voltage and density. This relation will be found useful in cases where the voltage is known at some one density and it is desired to estimate it for another density

¹ Sharp, C. H., *Electrical World*, 69, p. 556, 1917.

not too widely different. It is unsafe, however, to use this law of direct proportionality to extrapolate over a long range from the sparking voltage at normal atmospheric density to that at a very high density.

CONCLUSIONS.

These experiments confirm the relation that the breakdown voltage of a spark gap depends only upon the density of the gas and varies with pressure and temperature only as they affect the density. This relation is found to be valid up to 800° C. and 8 atmospheres pressure. Both the pressure and temperature of the charge in a gasoline engine increase very greatly during the compression stroke, but the sparking voltage can be computed from the linear relations shown in plot 5 without a knowledge of these variables separately, since the density is determined solely by the original density and the compression ratio. For small changes in density, as between engines of different compression ratios, the assumption that the voltage is proportional to the density may be made.

With the sudden discharge from an ignition coil or magneto a disruptive spark is produced even at temperatures where a 60-cycle voltage would produce a brush discharge.

The voltage required for a spark plug set at 0.5 mm. (0.020 inch) in an aviation engine of moderate compression is of the order of magnitude of 6,000 volts.

